

Low-threshold bistability of slow light in photonic-crystal waveguides

S. F. Mingaleev,¹ A. E. Miroshnichenko,² and Yu. S. Kivshar²

¹ *Bogolyubov Institute for Theoretical Physics of the National Academy of Sciences of Ukraine, 14-B Metrologichna Street, Kiev 03680, Ukraine*

² *Nonlinear Physics Centre and Centre for Ultra-high bandwidth Devices for Optical Systems (CUDOS), Research School of Physical Sciences and Engineering, Australian National University, Canberra ACT 0200, Australia*
mingaleev@htp.kiev.ua, aem124@rsphysse.anu.edu.au

Abstract: We analyze the resonant transmission of light through a photonic-crystal waveguide side coupled to a Kerr nonlinear cavity, and demonstrate how to design the structure geometry for achieving bistability and all-optical switching at *ultralow* powers in the *slow-light* regime. We show that the resonance quality factor in such structures scales inversely proportional to the group velocity of light at the resonant frequency and thus grows indefinitely in the slow-light regime. Accordingly, the power threshold required for all-optical switching in such structures scales as a square of the group velocity, rapidly vanishing in the slow-light regime.

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1. Introduction

Recent studies of slow light and its properties are motivated by the enhancement of light-matter interactions for smaller group velocities leading to the enhancement of optical gain [1] and electro-optic effect [2], a growth of the spontaneous emission rate [3], and more efficient nonlinear optical response [4, 5, 6, 7]. The concept of slow light is also useful for realizing all-optical routers and optical buffers for pulse storage and synchronization.

Different concepts and schemes for realizing the slow-light propagation in various media and structures have been suggested so far. Although the most dramatic reduction of the group velocity of light has been achieved in atomic media and it is based on electromagnetically-induced transparency, such media are not suitable for high-bit-rate optical systems due to their high dispersion [8]. In contrast, alternative realizations of the slow-light propagation in high-index-contrast coupled resonator structures can be very useful for creating optical buffers operating at hundreds of gigabits/s [8]. Recently, ultra-compact coupled-resonator optical buffers on a silicon chip have been experimentally fabricated with a large fractional group delay exceeding 10 bits, achieved for bit rates as high as 20 gigabits/s [9].

Compact coupled-resonator optical systems can be realized on the basis of photonic-crystal waveguides, for which the slow-light propagation with the smallest achieved group velocity reaching $c/1000$ has been experimentally demonstrated [10, 11, 12, 13]. Because of this success, the interest to the slow-light applications based on photonic-crystal waveguides is rapidly

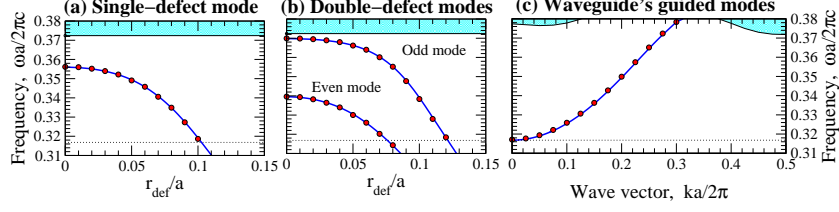


Fig. 1. Frequencies of localized cavity modes created by changing the radius r_{def} of (a) a single defect rod, and (b) two neighboring defect rods in the photonic crystal created by a triangular lattice of rods with $\epsilon = 12$ and radius $r = 0.25a$ in air, a is the lattice spacing. (c) Dispersion of the W1 photonic-crystal waveguide created by removing a row of rods in the same photonic crystal. Results are calculated using eleven maximally localized Wannier functions [27] (blue lines) in an excellent agreement with the supercell plane-waves method [28] (red circles).

growing, attracting attention to the problems of designing waveguide bends [14], couplers [15], and other types of functional optical devices which would efficiently operate in the slow-light regime.

Dynamic control of the slow-light propagation can be realized by direct tuning of the group velocity, either thermo-electrically [12] or all-optically [16]. The scales of the corresponding optical devices are, however, sub-optimal. Potentially, they can be reduced dramatically in the waveguide-cavity structures with tunable high-quality resonances [17]. Using a nonlinear cavity, active switching and other functionalities of such devices can be realized by shifting the resonance frequency all-optically, e.g. by changing the power of the incoming light in order to achieve the bistable transmission. Several successful experimental realizations of low-threshold light switching in such structures have been recently reported [18, 19, 20, 21, 22, 23, 24]. However, none of those demonstrated devices could operate in the slow-light regime.

Making the waveguide-cavity structures to be applicable and useful for the dynamic control of the slow-light propagation is a nontrivial task, due to strong extrinsic scattering losses caused by most types of side-coupled cavities (including those introduced by fabrication imperfections) for operating frequencies close to the edges of the propagation bands [25, 26].

In this paper, we demonstrate how to employ the recently suggested geometry-based enhancement of the resonance quality factor [26] to design efficient waveguide-cavity structures for ultralow-threshold bistability and all-optical switching in the slow-light regime.

The outline of the paper is as follows. Section 2 describes the model we adopt, using the single-defect geometry shown in Fig. 2 as a concrete example, and demonstrates why such type of geometry exhibits the resonance quality factor $Q \sim v_g$ which scales linearly with the group velocity of light, v_g , and thus vanishes at *both* propagation band edges. Section 3 describes the contrasting mechanism of slow light scattering which leads to $Q \sim 1/v_g$ growing indefinitely at one of the propagation band edges. Correspondingly, the power threshold P_{th} required for all-optical light switching decreases as $P_{\text{th}} \sim Q^{-2} \sim v_g^2$ in this case. We illustrate this mechanism on the example of the double-defect geometry shown in Fig. 3. Section 4 concludes the paper.

2. Model and the basic parameters

To illustrate our basic idea, we consider the simplest case of a two-dimensional photonic crystal (PhC) created by a triangular lattice of dielectric rods in air. The rods are made of either Si or GaAs ($\epsilon = 12$) with the radius $r = 0.25a$, a is the lattice spacing. Such photonic crystal has two large band gaps for the E-polarized light (electric field parallel to the rods), and we use the first gap between the frequencies $\omega a/2\pi c = 0.2440$ and 0.3705 . By reducing the radius of

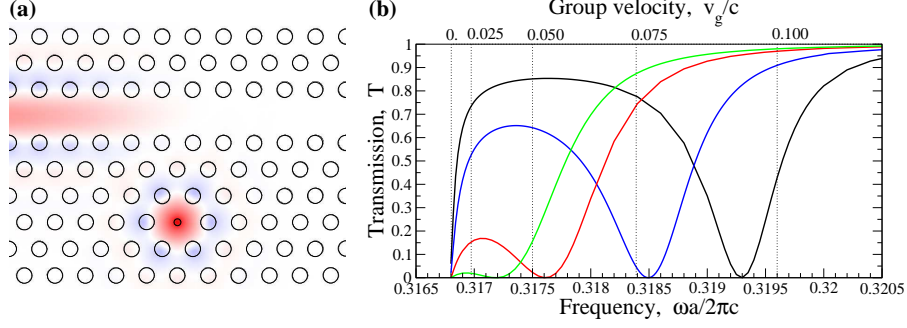


Fig. 2. Single-defect waveguide-cavity structure with the radius of the defect rod r_{def} : (a) Electric field at the resonance reflection for $r_{\text{def}} = 0.102a$; (b) Transmission spectra for different values of r_{def} : $0.1a$ (black), $0.101a$ (blue), $0.102a$ (red), $0.1025a$ (green). For convenience, in addition to the light frequency on the bottom axis, we indicate on the top axis the complementary group velocity, $v_g(\omega)$, of the waveguide's guided mode.

a single rod, we create a monopole-like localized defect mode in this bandgap [see Fig. 1(a)]. Reducing the radius of *two neighboring rods* allows to create two localized modes, one with odd and another with even field symmetry [see Fig. 1(b)]. Removing a row of rods creates the so-called W1-waveguide which guides light with the frequencies $\omega(k)$ determined by the guided mode wave vector k as shown in Fig. 1(c). The group velocity $v_g = d\omega/dk$ of the guided mode vanishes at the edge $k = 0$ (with $\omega a/2\pi c = 0.3168$) of the propagation band. At small wave vectors $(ka/2\pi) < 0.1$, it can be approximated as: $v_g/c \approx 1.8155(ka/2\pi) - 0.94776(ka/2\pi)^2$. All numerical results presented in this paper are obtained by employing the Wannier functions approach [27] using eleven maximally localized Wannier functions; they have also been checked to be in an excellent agreement with the results based on the plane-waves calculations [28].

First, we emphasize that in general case light transmission at the band edges of PhC waveguide structures is vanishing, due to vanishing group velocity v_g . This effect is responsible, in particular, for strong (scaling as $1/v_g$) extrinsic scattering loss of slow light in PhC waveguides due to random fabrication imperfections such as surface roughness and disorder [25].

To illustrate, in Fig. 2 we present the slow-light transmission spectra for the waveguide-cavity structure based on the W1-waveguide coupled to a cavity created by a single defect rod with the radius r_{def} . In what follows we refer to this structure as a single-defect geometry. Changing r_{def} , we shift the resonance frequency ω_{res} of this structure from the middle of the propagation band, at $r_{\text{def}} = 0$, to the edge ($k = 0$) at $r_{\text{def}} \approx 0.103a$. As was mentioned above, for such a generic structure the light transmission vanishes at the propagation band edges (at $\omega a/2\pi c = 0.3168$ in our case). This effect can be understood by analyzing an effective discrete model of the waveguide-cavity structures [26, 29]. In such discrete model the transmission coefficient can be calculated as $T(\omega) = \sigma^2(\omega)/[\sigma^2(\omega) + 1]$, where the function $\sigma(\omega)$ is determined by the structure geometry. For a high-quality resonance with ω_{res} lying deeply inside the propagation band $\sigma(\omega) \simeq \sigma_{\text{Lorenz}}(\omega) \equiv 2Q(1 - \omega/\omega_{\text{res}})$ is determined by the resonance quality factor Q . However, $\sigma(\omega)$ changes substantially near the band edges $k = 0$ and $k = \pi/s$, where s is the waveguide period ($s = a$ for the W1 waveguide). For most of the structures, $\sigma(\omega)$ can be approximated as $\sigma(\omega) \simeq \sin(ks)\sigma_{\text{Lorenz}}(\omega) \sim v_g\sigma_{\text{Lorenz}}(\omega)$ and, therefore, the transmission coefficient *vanishes at the band edges*, where $v_g \rightarrow 0$. This effect can be understood as an effective reduction of the quality factor $Q \sim v_g$ in the slow-light regime, clearly seen in Fig. 2. Moreover, when the resonance frequency approaches the band edge, the maximally achievable

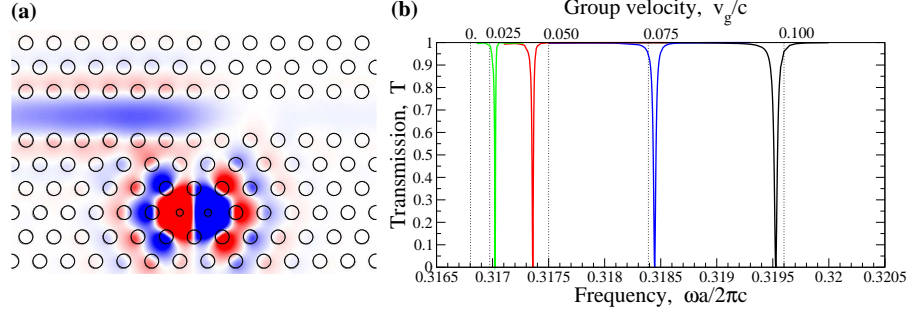


Fig. 3. Double-defect waveguide-cavity structure with the cavity created by two defect rods with the radius r_{def} : (a) Electric field at the resonance reflection for $r_{\text{def}} = 0.121a$; (b) Transmission spectra for different values of r_{def} : 0.119a (black), 0.120a (blue), 0.121a (red), 0.1213a (green).

(in the slow-light region) transmission vanishes too (see Fig. 2). Therefore, this structure cannot be employed for the slow-light switching because the optical bistability in such structures will become possible only [26, 30] when the linear transmission exceeds 75%.

3. Quality factor enhancement and slow-light bistability

We found that the effect of vanishing light transmission at the band edges of PhC waveguides is very common, and it appears in a variety of commonly used resonant structures. However, using the discrete nature of PhCs, it becomes possible to design such waveguide-cavity structures for which $\sigma(\omega) \simeq \tan(ks/2)\sigma_{\text{Lorenz}}(\omega)$ will grow inversely proportional with the vanishing group velocity, $\sigma(\omega) \sim (1/v_g)\sigma_{\text{Lorenz}}(\omega)$, at the band edge $k = \pi/s$ [26]. At this band edge $T \rightarrow 1$ and the effective quality factor of the resonance should grow as $Q \sim 1/v_g$ when the resonant frequency approaches the band edge. This increase in Q leads to significant lowering of the bistability threshold for all-optical light switching in the slow-light regime. Such a structure can be designed by placing a side-coupled cavity between two nearest defects of a PhC waveguide assuming that all the defect modes and the cavity mode have the same symmetry. In Ref. [26], we illustrated these results for the so-called coupled-resonator waveguides made by removing every second rod; this example looks however a bit artificial having limited applicability.

Our extensive analysis shows that the geometry engineering can be employed effectively to achieve the slow-light switching in different types of PhC structures, including the important case of the W1 waveguide and the propagation band edge at $k = 0$. In a general case, this approach is based on placing a side-coupled cavity with an appropriate symmetry of the cavity mode into special locations along the PhC waveguide. These locations and the mode symmetry should be chosen in such a way that the overlap between the cavity mode and guided mode at the band edge vanishes and, consequently, scattering of light by the resonator at this band edge vanishes too. As we already indicated, in the case when the waveguide's defect modes have the same symmetry as the cavity mode, such a vanishing of the modes' overlap is only possible at the band edge $k = \pi/s$, leading to $\sigma(\omega) \simeq \tan(ks/2)\sigma_{\text{Lorenz}}(\omega)$. However, as can be shown by direct extending of the results of the discrete model [29, 26], in the case of the opposite (even-odd) symmetry of the waveguide defect modes and the side-coupled cavity mode, such a vanishing of the modes' overlap becomes possible at the band edge $k = 0$, leading to $\sigma(\omega) \simeq \cot(ks/2)\sigma_{\text{Lorenz}}(\omega)$. Therefore, in this case both $\sigma(\omega)$ and the resonance quality factor grow inversely proportional with vanishing group velocity at the band edge $k = 0$: $\sigma(\omega) \sim (1/v_g)\sigma_{\text{Lorenz}}(\omega)$; and, therefore, we obtain $Q \sim 1/v_g$.

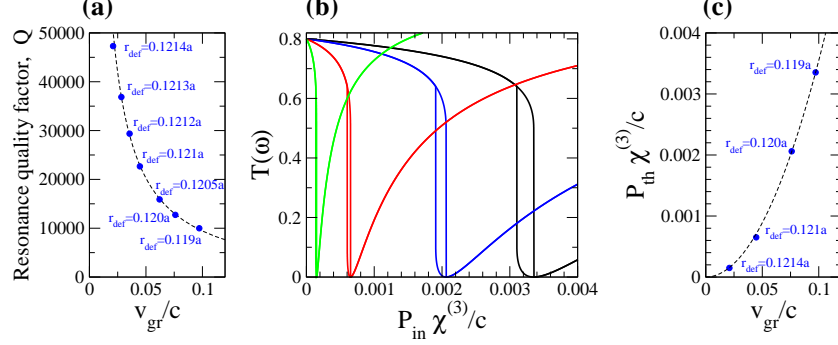


Fig. 4. (a) Quality factor Q vs. group velocity v_g at resonance for the structure shown in Fig. 3; (b) Nonlinear bistable transmission in the same structure at the frequencies with 80% of linear light transmission vs. the incoming light power for different values of r_{def} : 0.119a (black), 0.120a (blue), 0.121a (red), 0.1214a (green); (c) Switch-off bistability threshold P_{th} vs. the group velocity v_g at resonance for the same structure.

This is exactly the case of the waveguide-cavity structure presented in Fig. 3 which utilizes odd-symmetry mode of a double-defect cavity. Indeed, we use the even-symmetry defect modes creating the waveguide and thus to achieve high- Q resonance in the slow-light regime at the band edge $k = 0$ we should employ a side-coupled cavity mode with the odd symmetry. The simplest cavity of this type is created by reducing the radius r_{def} of *two neighboring rods*, as shown in Figs. 1(b). The range of the resonance frequencies of such a structure occupies almost the whole propagation band from its upper boundary at $r_{def} = 0$ to its edge $k = 0$ at $r_{def} \approx 0.1215a$. In Fig. 3 we present the linear transmission spectra for several values of the radius r_{def} . As is seen, in all the cases the light transmission remains perfect at the band edge $k = 0$ due to decoupling guided and cavity modes [26, 29]. The resonance quality factor Q grows when the resonance frequency approaches the band edge. Numerically obtained dependence $Q(v_{gr}) \sim 1/v_{gr}$ is shown in Fig. 4(a), and it is in an excellent agreement with the theoretical predictions. Since the bistability threshold power of the incoming light in waveguide-cavity structures scales as $P_{th} \sim 1/Q^2$ [26], we should observe rapid vanishing of $P_{th} \sim v_g^2$ when the resonance frequency approaches the band edge. Indeed, direct numerical calculations summarized in Figs. 4(b,c) prove this idea. These results were calculated with the straightforward nonlinear extension of the Wannier function approach [27] using 11 maximally localized Wannier functions.

4. Conclusions

We have analyzed the resonant transmission and bistability of slow light in a photonic-crystal waveguide coupled to a nonlinear cavity. We have shown how to achieve the perfect transmission near the edges of the propagation band by adjusting either the cavity location relative to the waveguide or the mode symmetry. We emphasize that such properly designed photonic structures are suitable for the observation of high- Q resonant (with the quality factor $Q \sim 1/v_g$) and ultralow-threshold bistable (with threshold power $P_{th} \sim v_g^2$) transmission of slow light with the small group velocity v_g at the resonance frequency. Thus, engineering the geometry and mode symmetry of the photonic-crystal structures is an useful tool for developing novel concepts of all-optical switching devices operating in the slow-light regime.

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